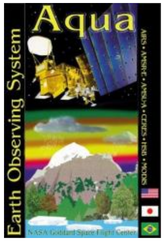
Multi-Species, Multi-Spectral, Multi-Satellite retrievals of trace gases

Vivienne Payne[1], Dejian Fu[1], Susan Kulawik[2], Kevin Bowman[1], Kazuyuki Miyazaki[3]

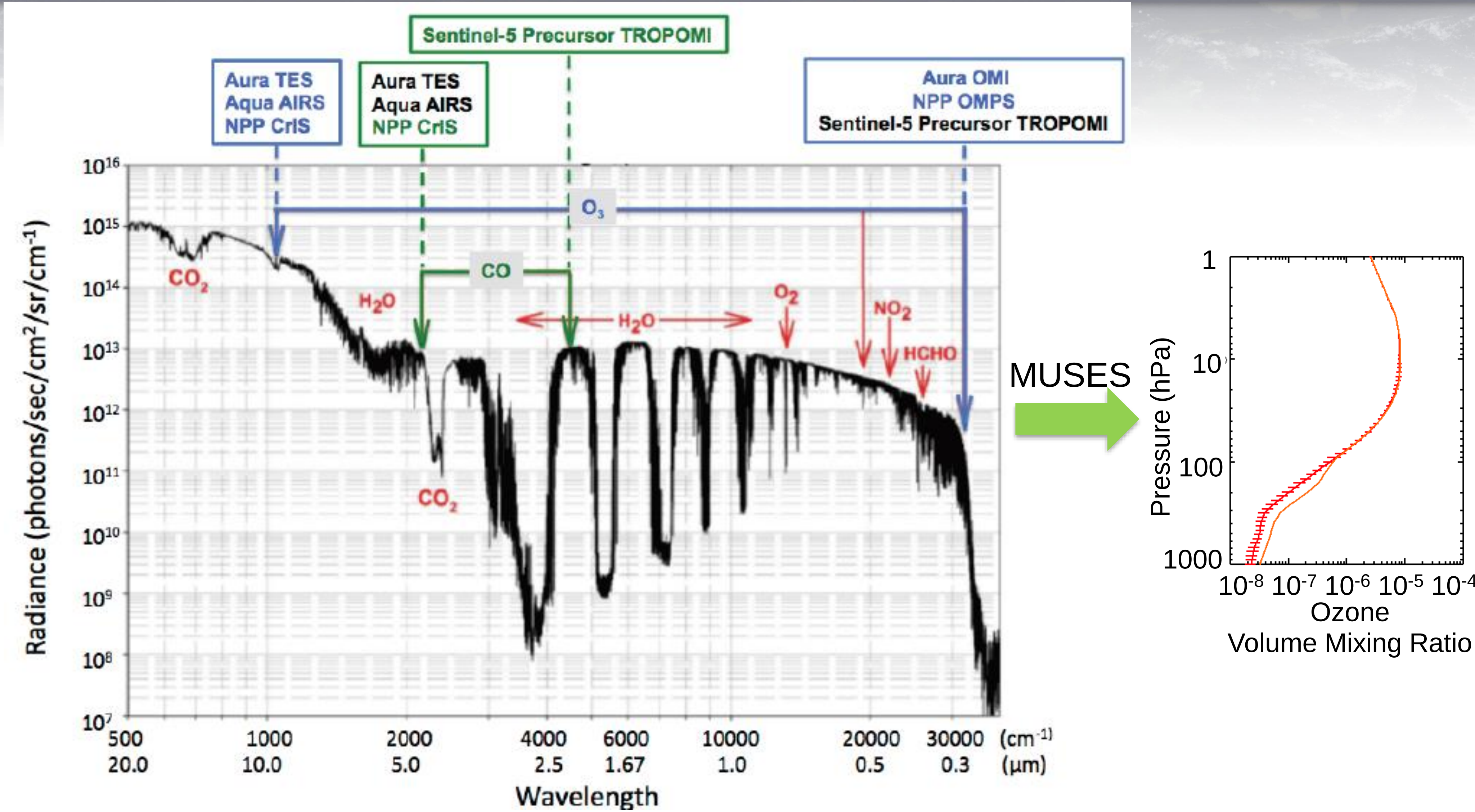
With special thanks to:

Helen Worden[4], Karen Cady-Pereira[5], Dylan Millet[6], Kelley Wells[6], Emily Fischer[7], Shashan Yu[1], Jessica Neu[1], John Worden[1], Larry Flynn[8], Yong Han[8], Larrabee Strow[9], Evan Fishbein[1], Bill Irion[1], Vijay Natraj[1] and to the TES, AIRS, OMI, CrIS, OMPS, TROPOMI teams

01 NASA Jet Propulsion Laboratory, California Institute of Technology
02 NASA Ames Research Center
03 Japan Agency for Marine-Earth Science and Technology
04 National Center for Atmospheric Research
05 Atmospheric and Environmental Research
06 University of Minnesota
07 Colorado State University
08 NOAA Center for Satellite Applications and Research, USA
09 University of Maryland Baltimore County, USA



Spectral Regions Used in JPL MUSES (Multi-Spectra, Multi-Species, Multi-Sensors) Algorithm



Measurements from TIR (LW) are sensitive to the free-tropospheric trace gases.
Measurements from UV-Vis-NIR (SW) are sensitive to the column abundances of trace gases.
Joint LW/SW measurements can distinguish upper troposphere from lower troposphere.

Retrieval characteristics and diagnostics

JPL MUSES algorithm delivers both retrieved trace gas concentration profiles and observation operators needed for trend analysis, climate model evaluation, and data assimilation.

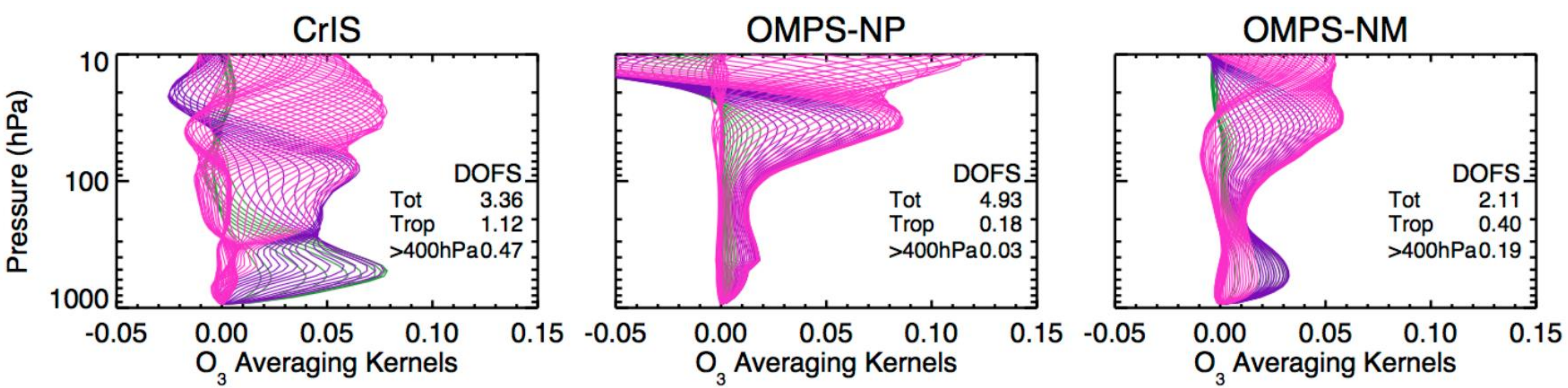
E.g., a data assimilation system applies an observation operator (**H**)

$$\mathbf{y}^s = \mathbf{H}(\mathbf{x}) = \mathbf{x}_a + \mathbf{A}(\mathbf{x}_{model} - \mathbf{x}_a)$$

$\mathbf{y}^s$ is the model profiles; $\mathbf{x}_a$ is *a priori* profiles used in the retrievals; **A** is the averaging kernels of satellite observations.

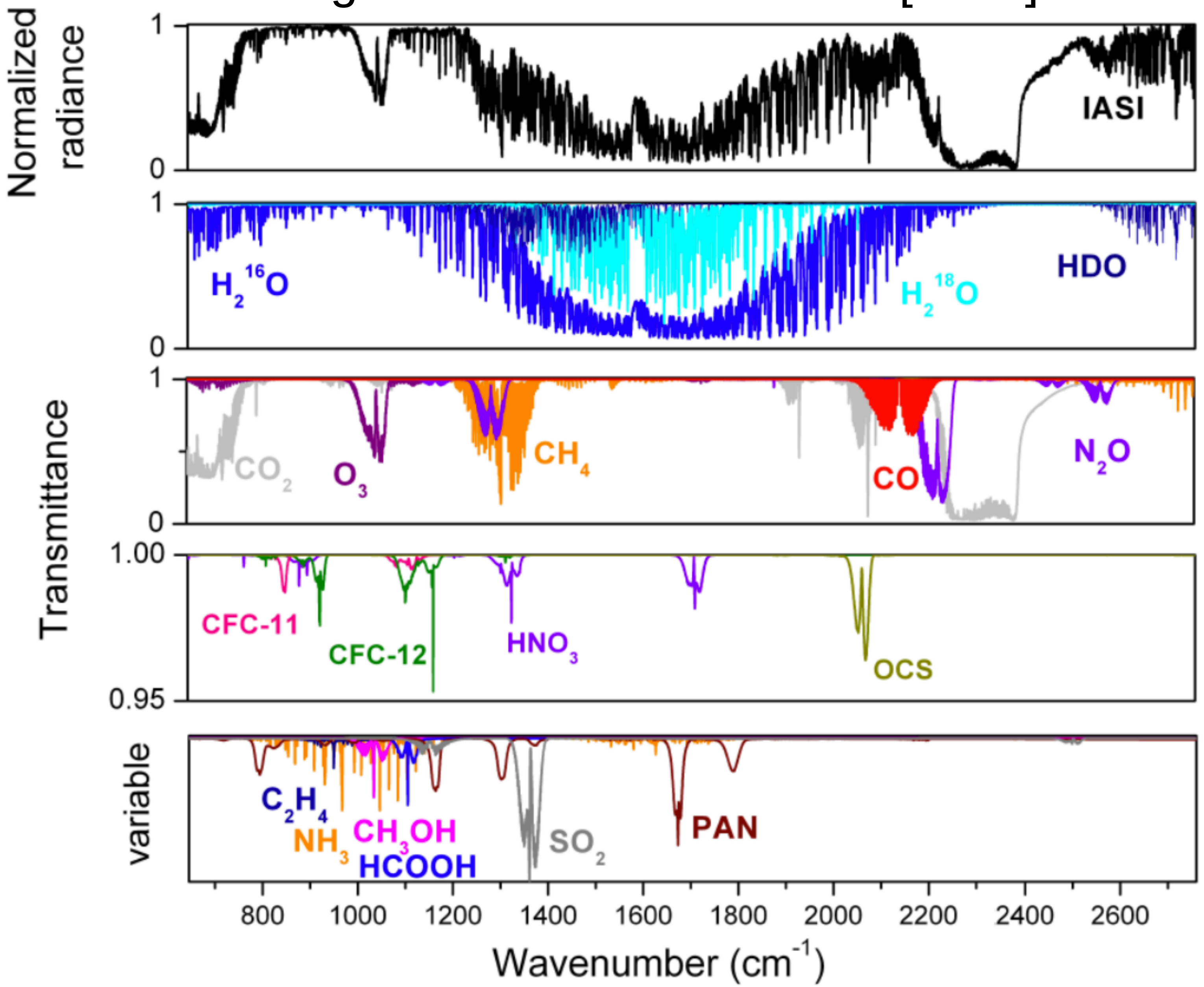
After applying observation operator to model profiles, the satellite-model differences ($\mathbf{y}^o$- $\mathbf{y}^s$) is not biased by the *a priori* used in the retrievals.

$$\Delta\mathbf{y} = \mathbf{y}^o - \mathbf{y}^s = \mathbf{A}(\mathbf{x}_{true} - \mathbf{x}_{model}) + \varepsilon$$



Thermal Infrared

Figure from Clerbaux et al. [2009]



Trace gas products from Aura-TES

TES version 7 trace gas products
Ozone (O_3)
O_3 Instantaneous Radiative Kernels
Carbon Monoxide (CO)
Methane (CH_4)
Carbon Dioxide (CO_2)
Nitrous Oxide (N_2O)
Deuterated Water Vapor (HDO)
Carbonyl Sulfide (OCS)
Ammonia (NH_3)
Peroxyacetyl Nitrate (PAN)
Formic Acid (HCOOH)*
Methanol (CH_3OH)

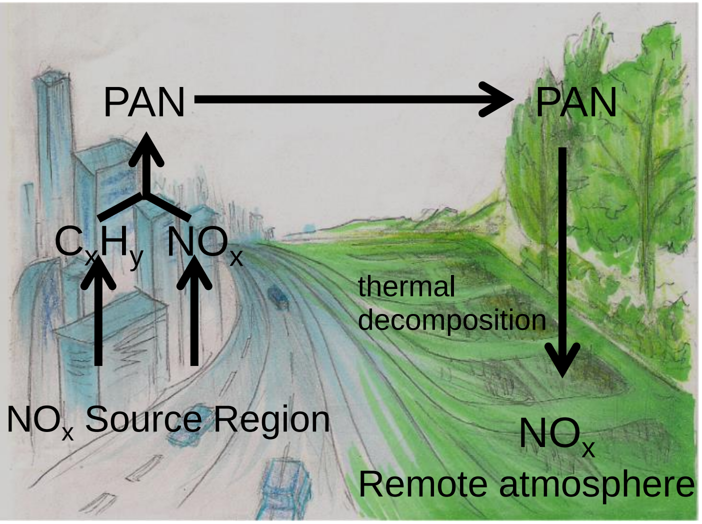
Omnipresent

Observable at enhanced concentrations

* Feature is in spectral gap for S-NPP CrIS

Peroxyacetyl nitrate (PAN)

- PAN plays key roles in
  - Long-range transport of ozone
  - Redistribution of nitrogen in the troposphere
- PAN is the **route for NO_x to reach the remote troposphere**
- PAN **couples biogenic emissions to the nitrogen cycle**, increasing the spatial range of NO_x
- PAN **extends the air quality impacts of fires**



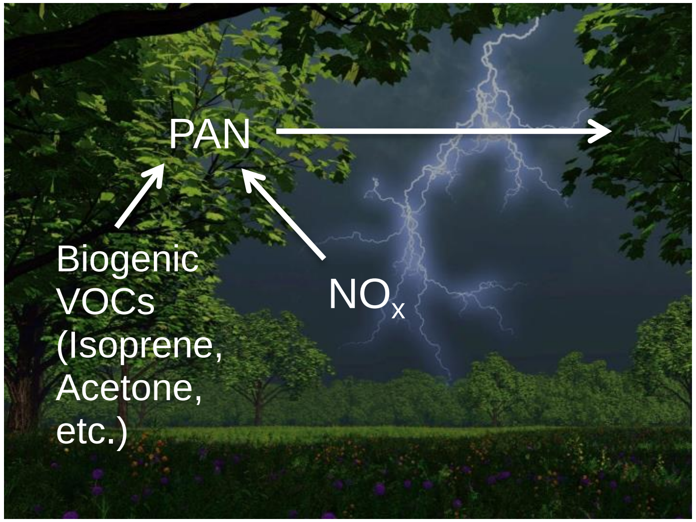
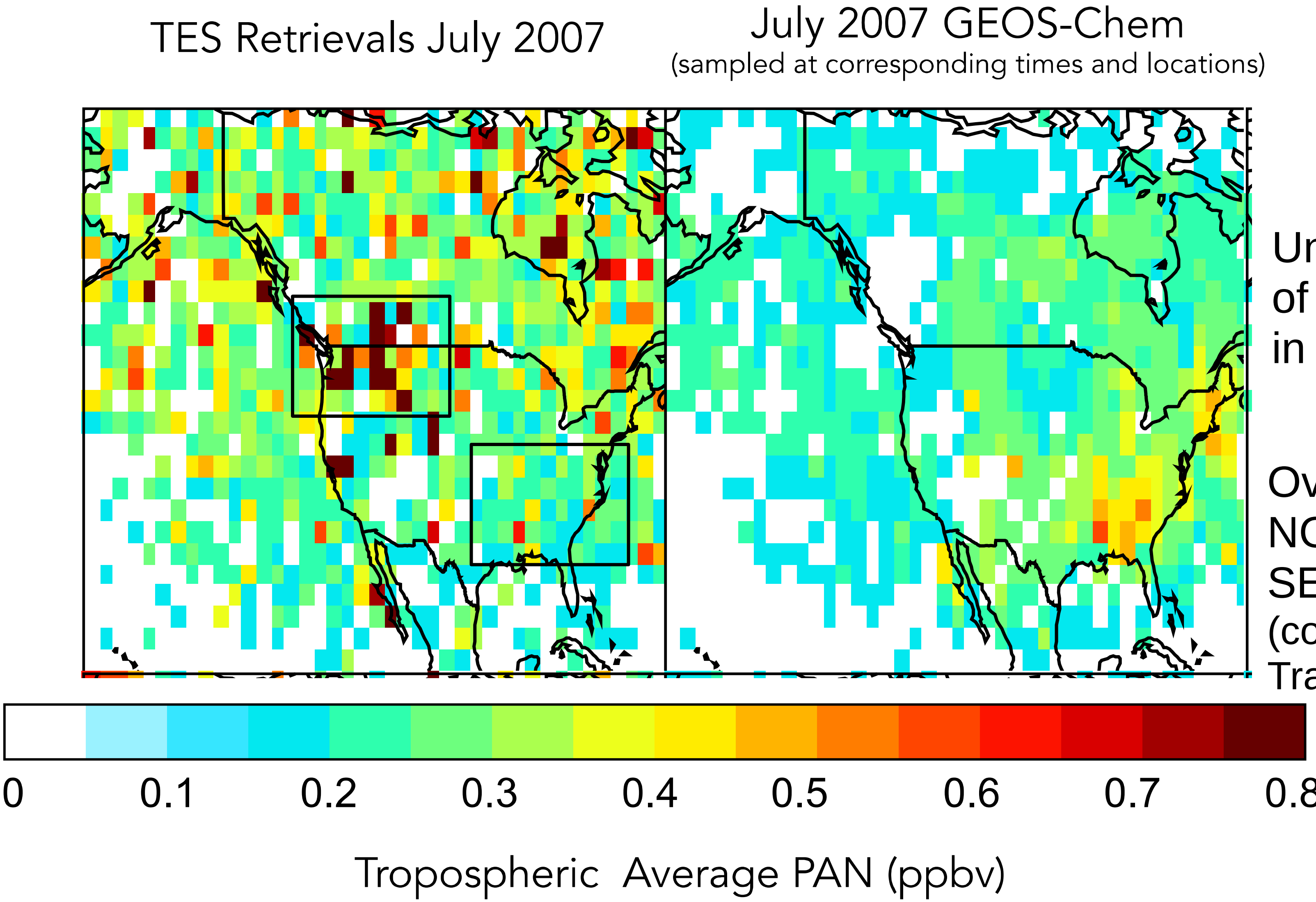


Photo of High Park Fire from CNN

PAN from TES

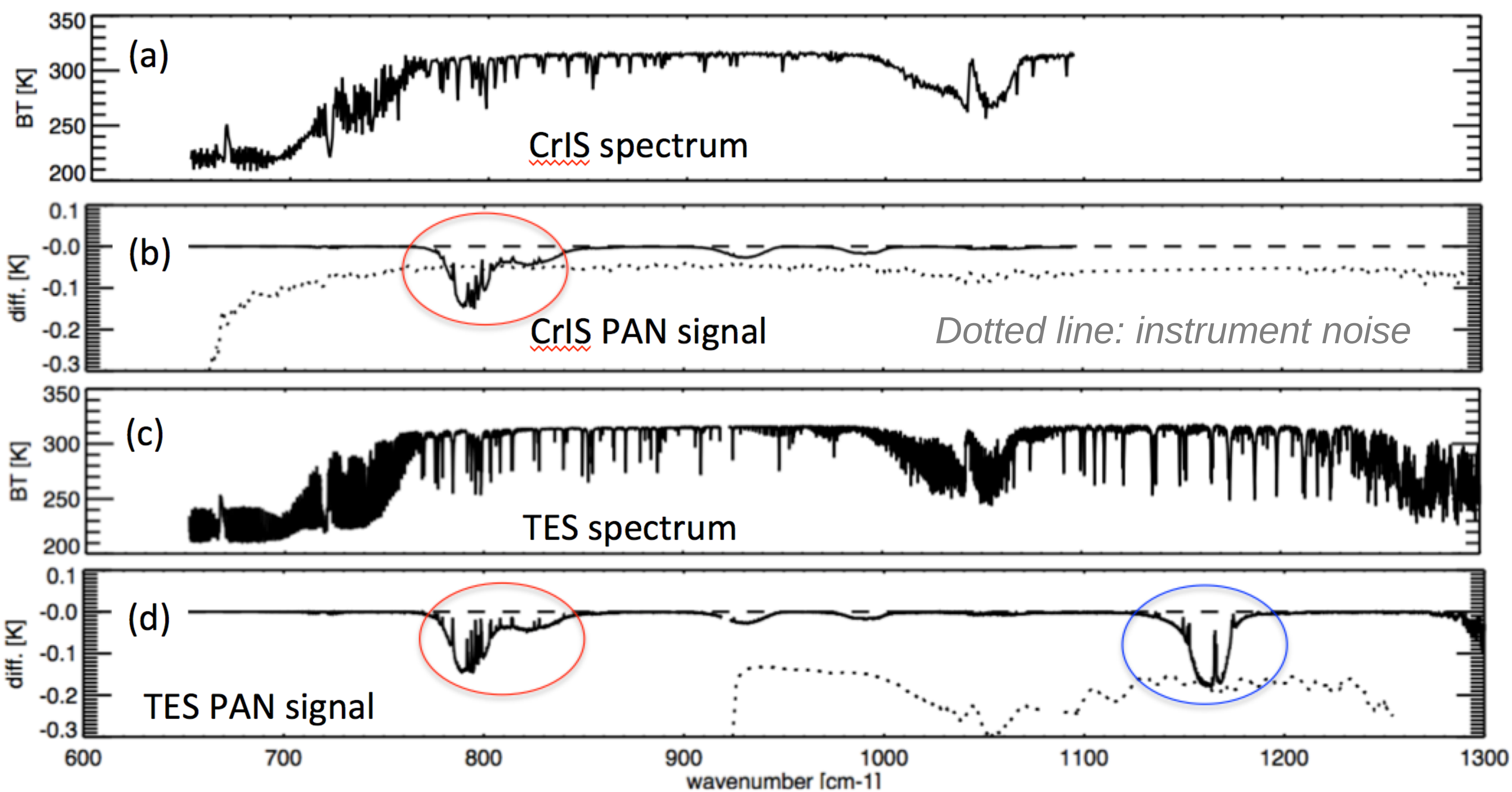


Underestimation of PAN from fires in NW US

Overestimation of NO_x emissions in SE US (consistent with Travis et al., 2016])

Fischer et al., in prep

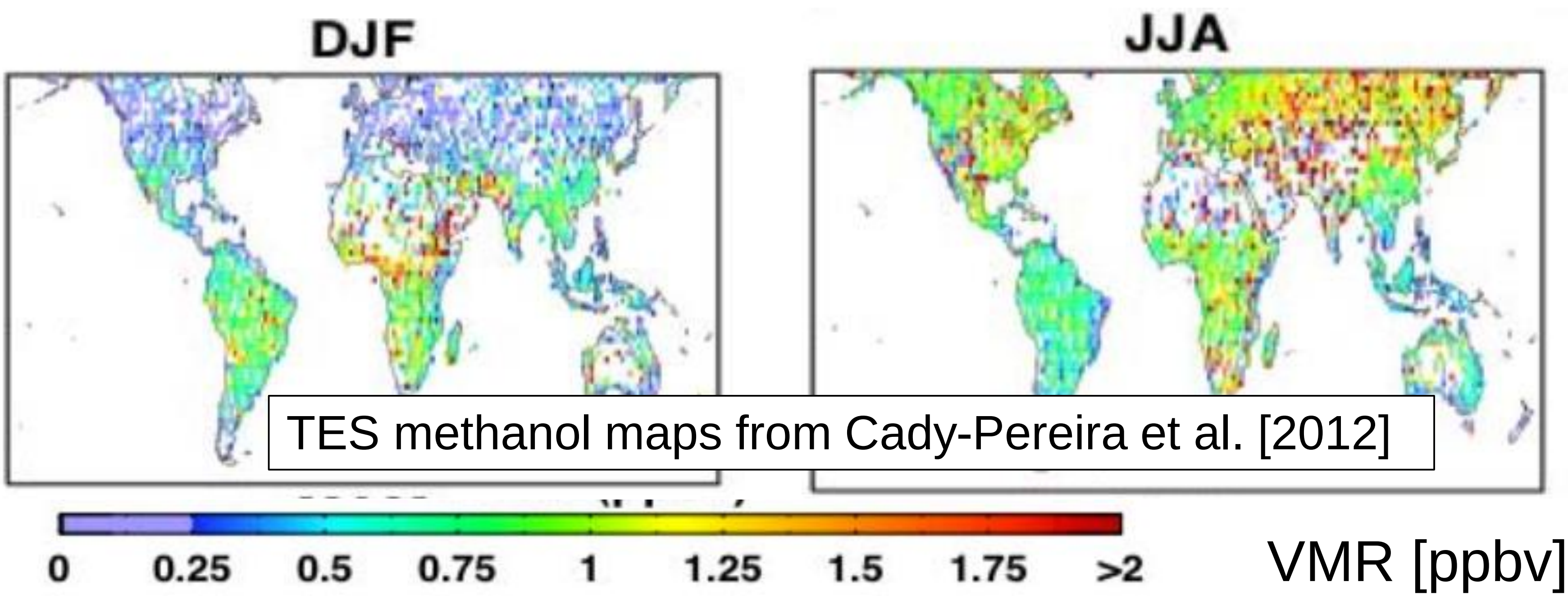
PAN from CrIS



- Opportunities offered by CrIS PAN compared to TES PAN:
  - Extension of TES record in time
  - Better signal to noise and drastically improved spatial coverage
  - **New constraints on chemical models at global and regional scales**

Methanol (CH_3OH)

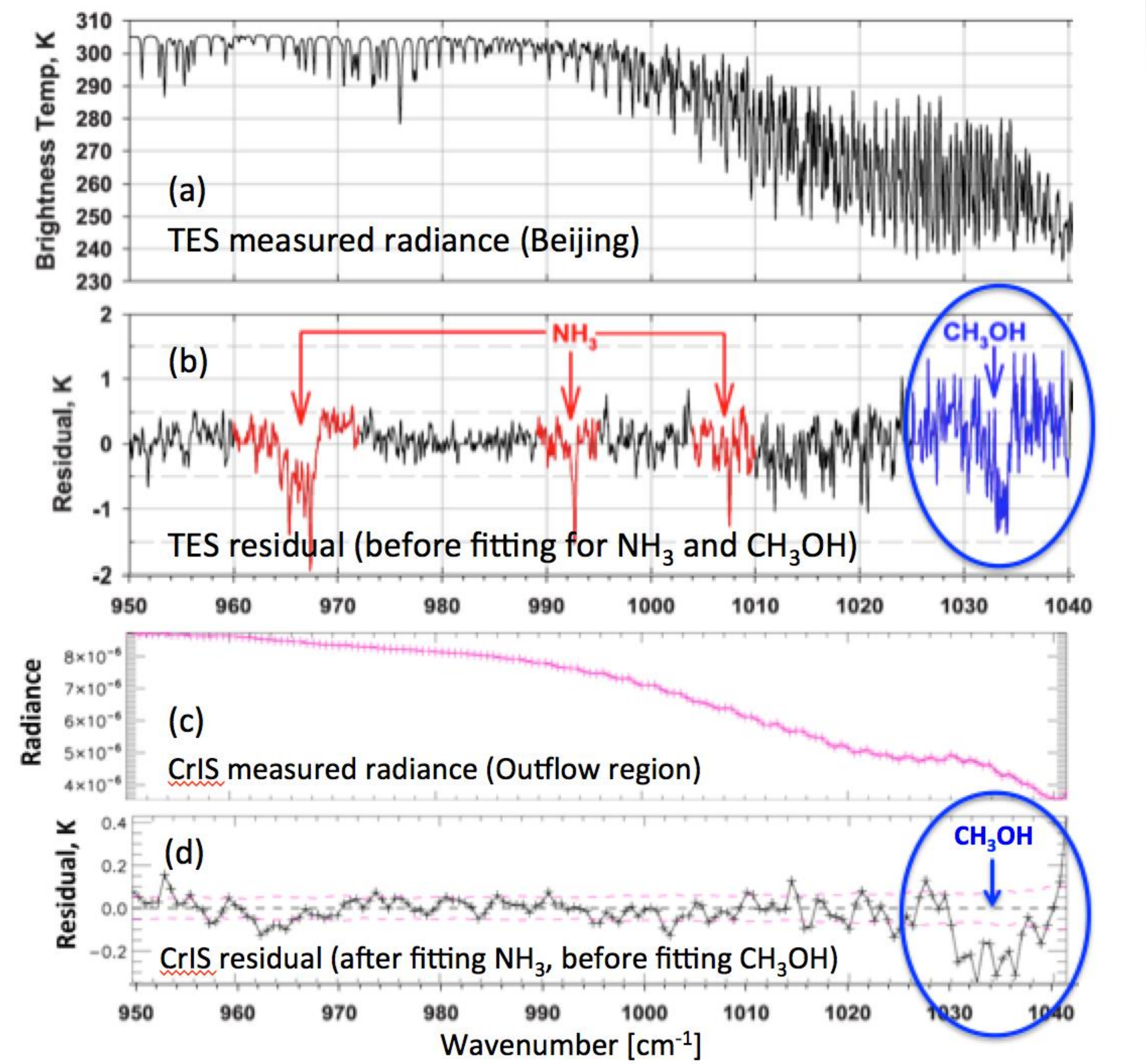
- Methanol is the most abundant NMVOC
  - Major source of carbon monoxide and formaldehyde
  - Leads to formation of ozone and secondary organic aerosols
- Methanol has both biogenic and combustion sources
  - Resolution of biogenic from other sources remains a challenge
  - Carbon monoxide can be used as a tracer, but CO also has biogenic sources
  - Value of tracers with no biogenic sources [e.g. acetylene (C_2H_2)]
    - Previous spaceborne obs of C_2H_2 from IASI (Duflot et al. [2013])
    - CrIS has lower noise than IASI.....



TES methanol maps from Cady-Pereira et al. [2012]

Methanol residuals

Methanol feature lies within the ozone band. Ozone must be fit first.



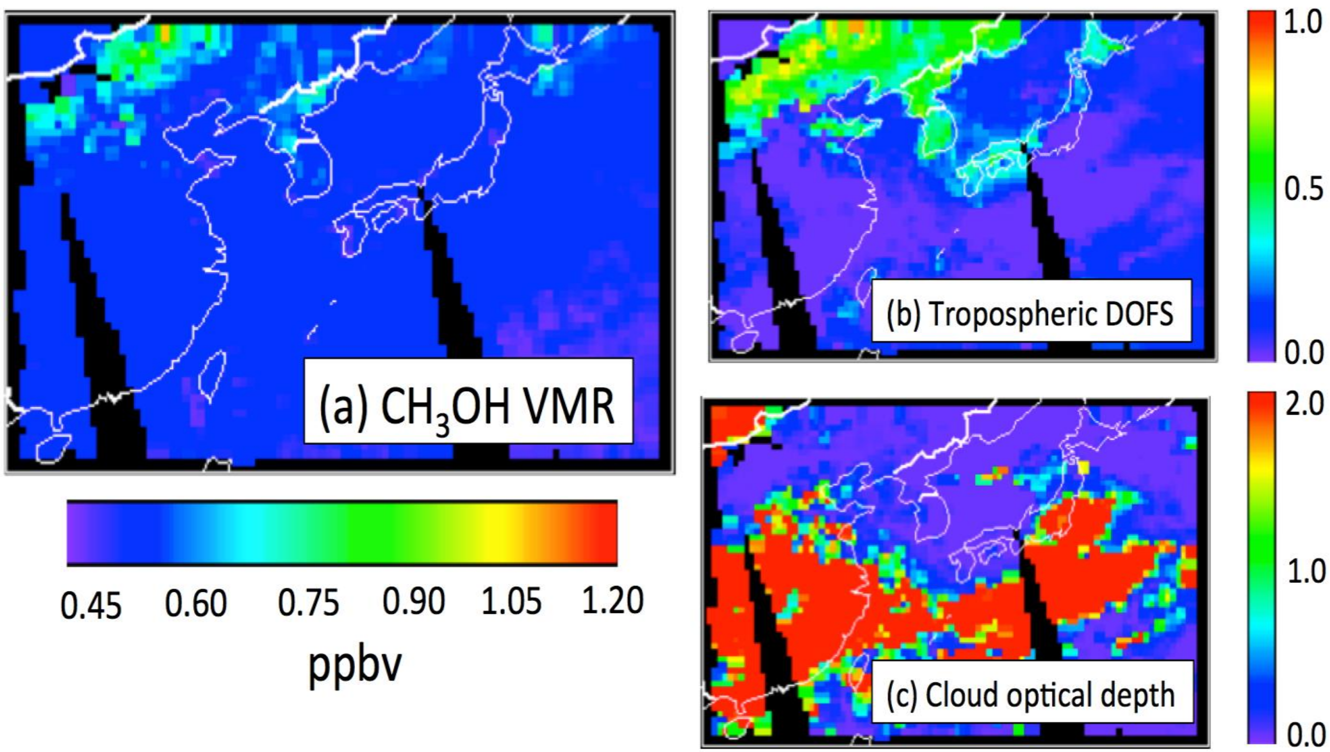
TES

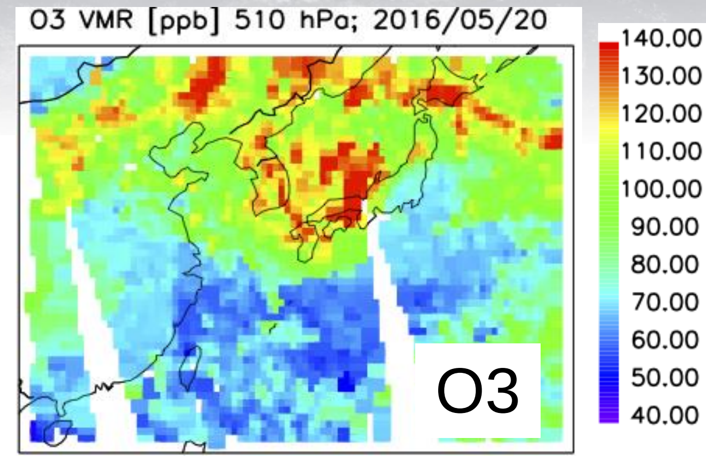
Plots from Beer et al. [2008]

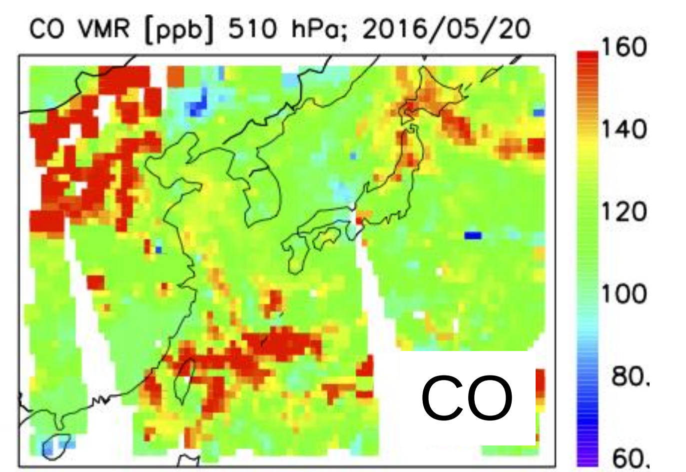
CrIS

Methanol retrievals from CrIS

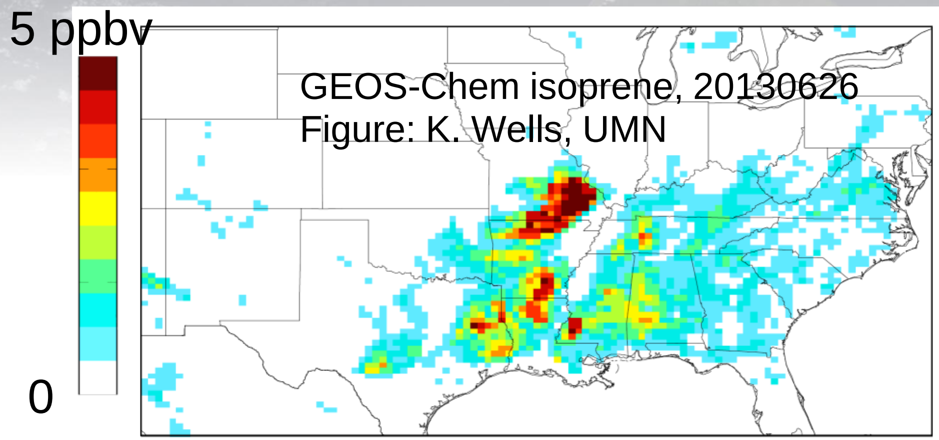
Methanol retrievals over KORUS-AQ domain

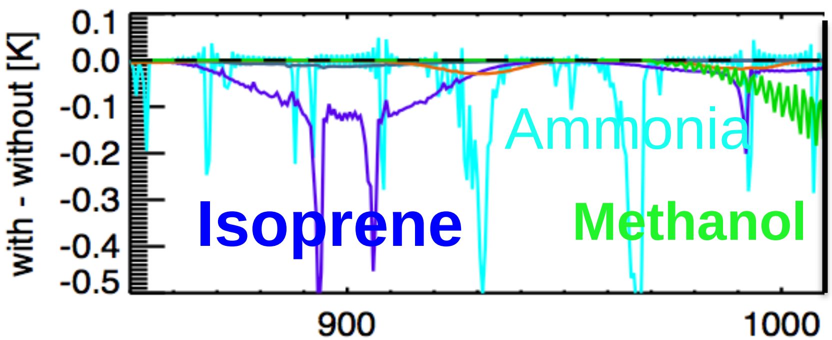






Isoprene from CrIS





- Isoprene:
  - Biogenic VOC, emitted by plants
  - Shapes tropospheric composition through impacts on ozone, aerosols, the atmosphere's oxidizing capacity and the nitrogen cycle

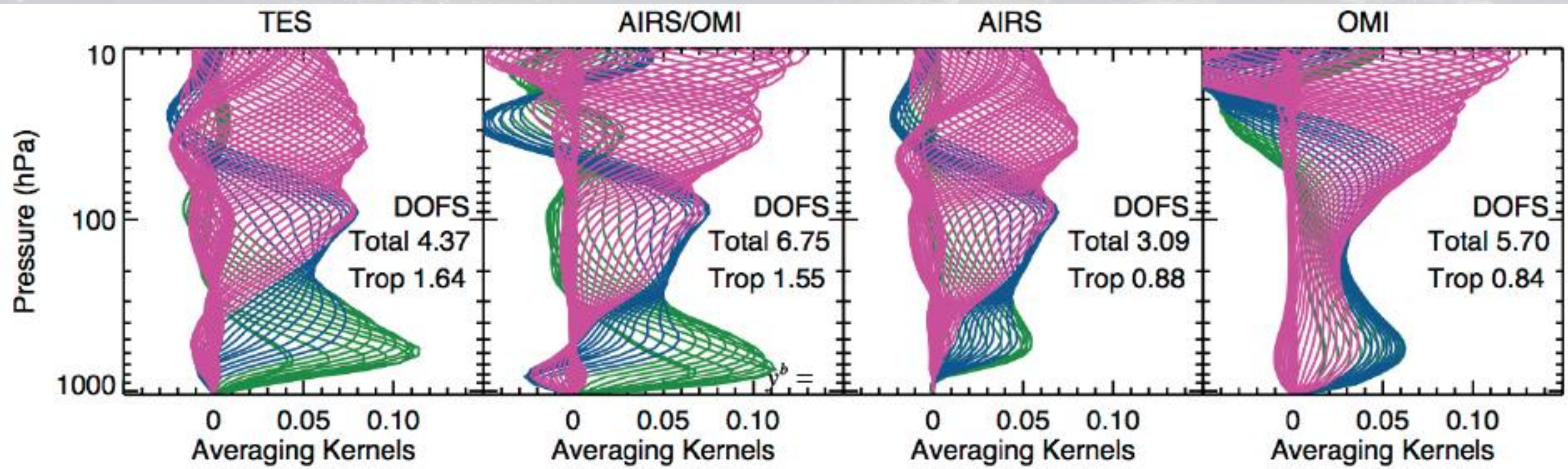
NASA Roses-funded activities:
(Aura ST/ACMAP Program)

Isoprene retrievals from CrIS (**Fu et al.**)

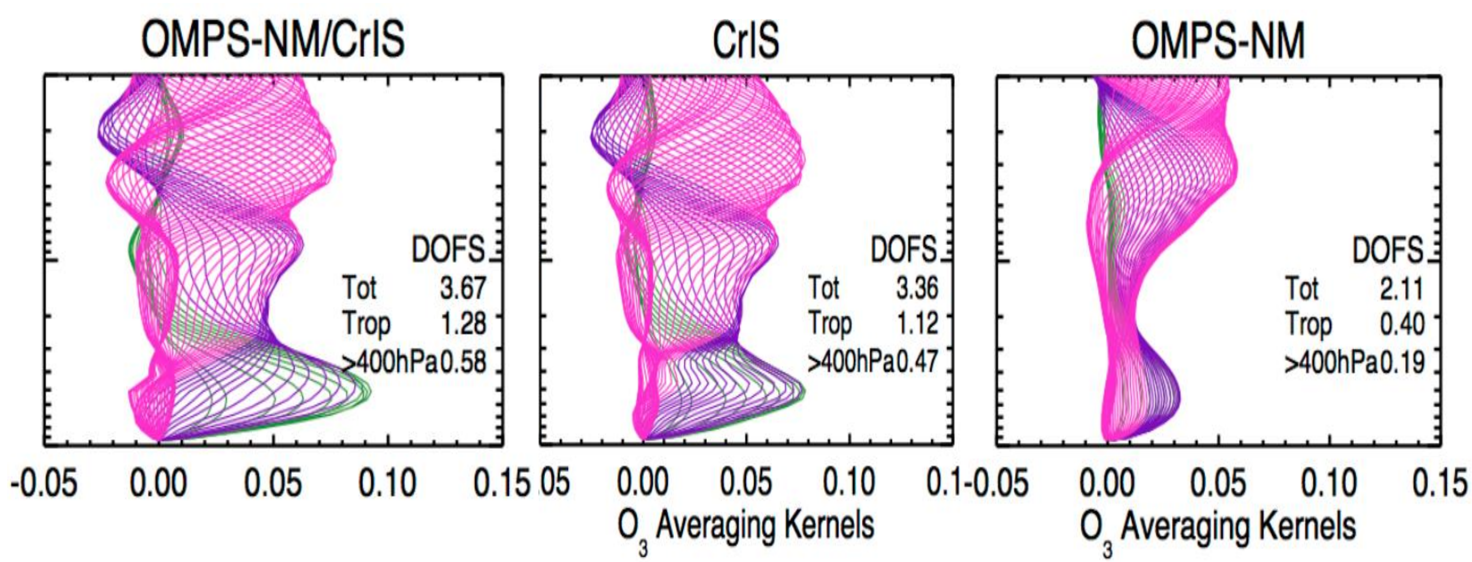
Combine CrIS isoprene, Aura OMI (HCHO, NO_2) and the GEOS-Chem model to advance understanding of isoprene oxidation and HCHO production across NO_x regimes. (**Millet et al.**)

Multi-spectral retrievals

Multi-spectral retrievals of ozone

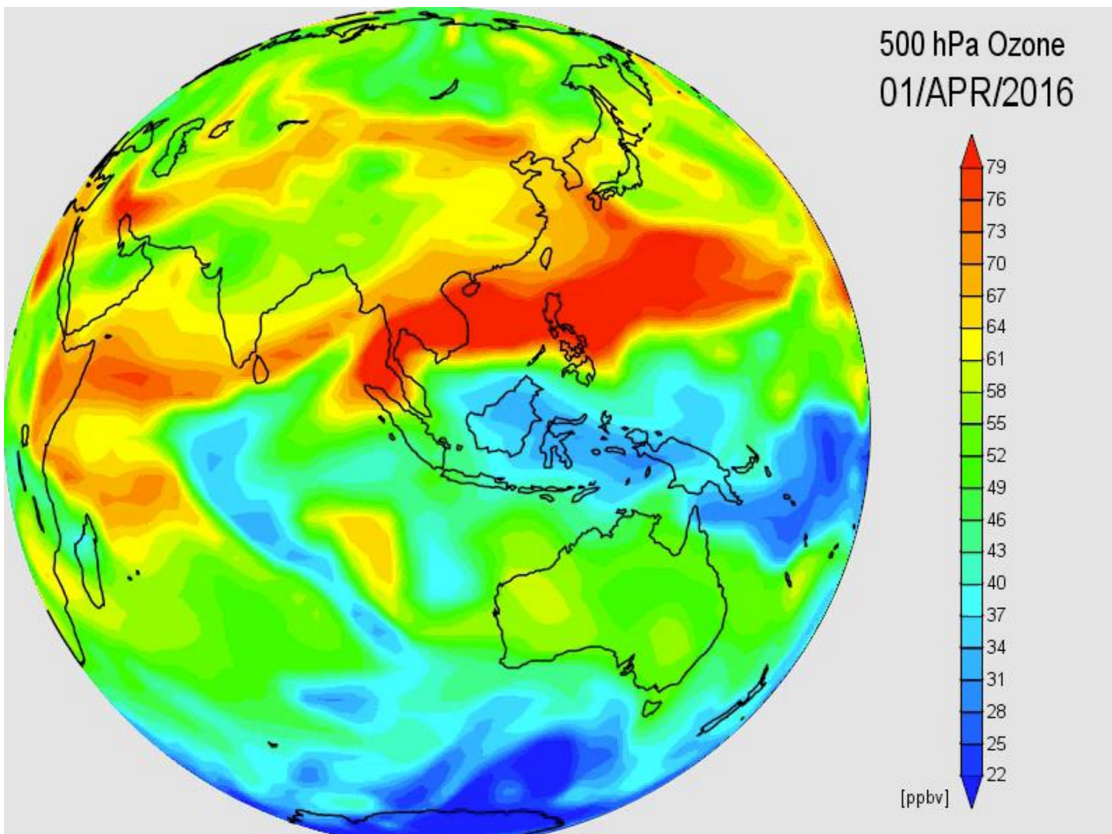


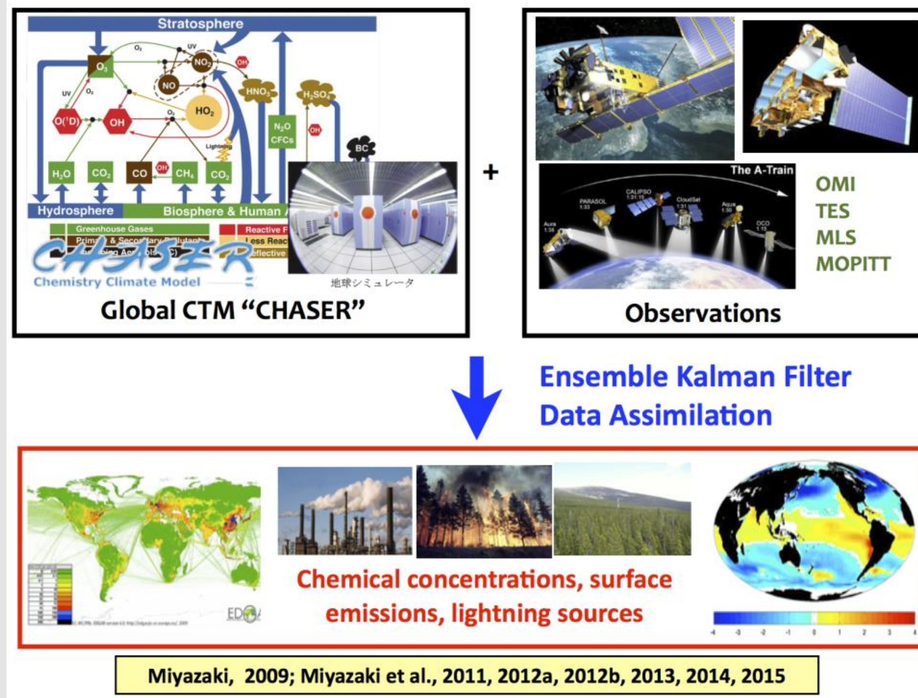
Multi-spectral retrievals can offer improved sensitivity to the lower troposphere



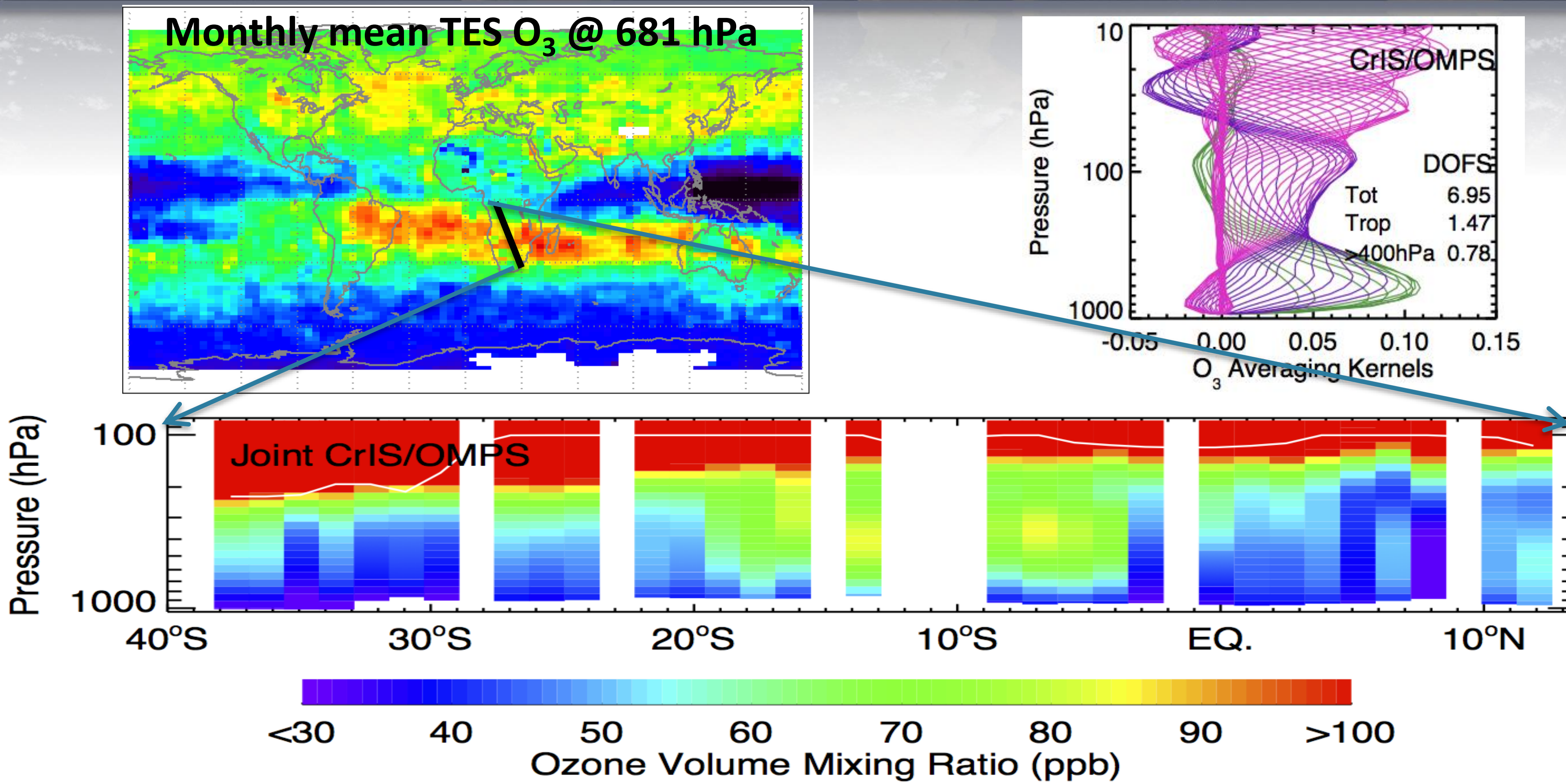
Assimilated Global Ozone Fields

- Joint AIRS/OMI ozone profiles have been assimilated into CHASER system.
- CHASER system assimilated the OMI (NO_2), GOME-2 (NO_2) MLS (HNO_3 and O_3), MOPITT (CO) for KORUS-AQ ,recently assimilated AIRS/OMI ozone profile data





Extension to Joint CrIS/OMPS O_3 Retrievals

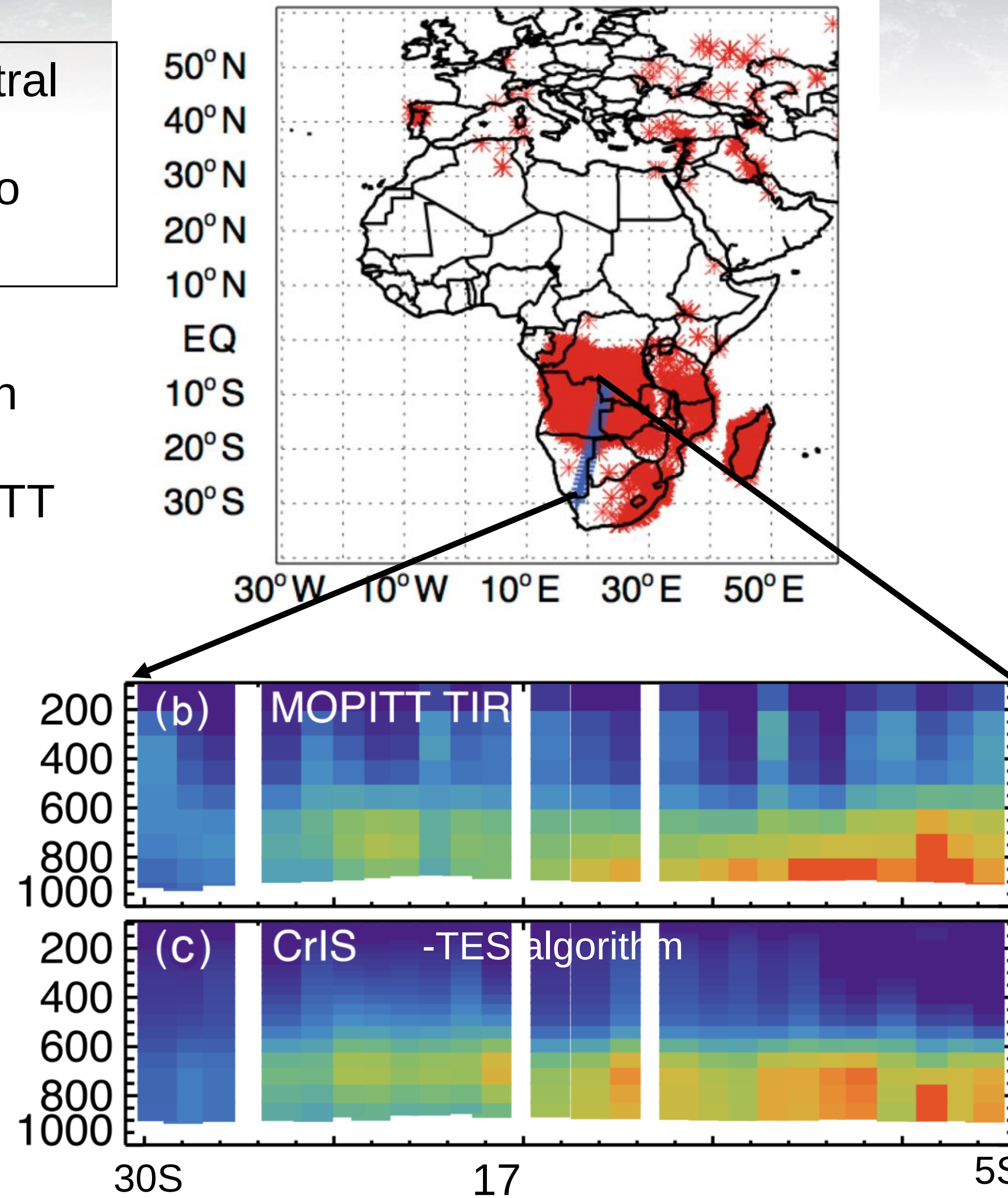


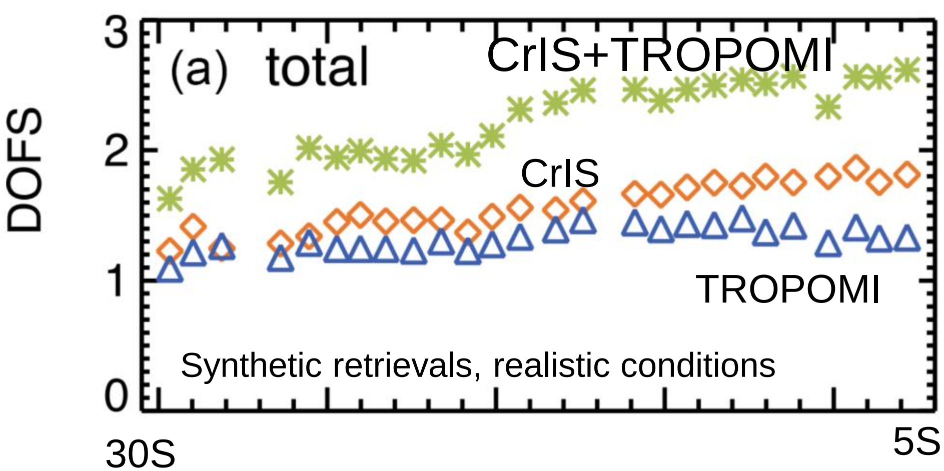
- MUSES has been applied to joint CrIS/OMPS ozone retrievals over Africa on October 21, 2013.
- The elevated ozone concentrations (2-20 degree south) are associated with biomass burning.
- **Joint CrIS/OMPS O_3 and CrIS CO retrievals using MUSES will support the NOAA FIREX flight campaign** (NOAA CPO AC4 program)
  - Assimilation within RAQMS (R. B. Pierce)

Multispectral CO from CrIS and TROPOMI

MOPITT's unique thermal IR/near IR multispectral CO measurements, which are able to separate near-surface from the free troposphere, have no planned follow-on.

Fu et al, AMT (2016): Combining CrIS data with the Sentinel 5p TROPOMI near IR data would provide comparable vertical sensitivity to MOPITT but with daily coverage.





Summary

- Suomi-NPP and JPSS offer many exciting opportunities for advancing understanding of tropospheric composition and chemistry

- Value of multiple species for constraints on chemical models

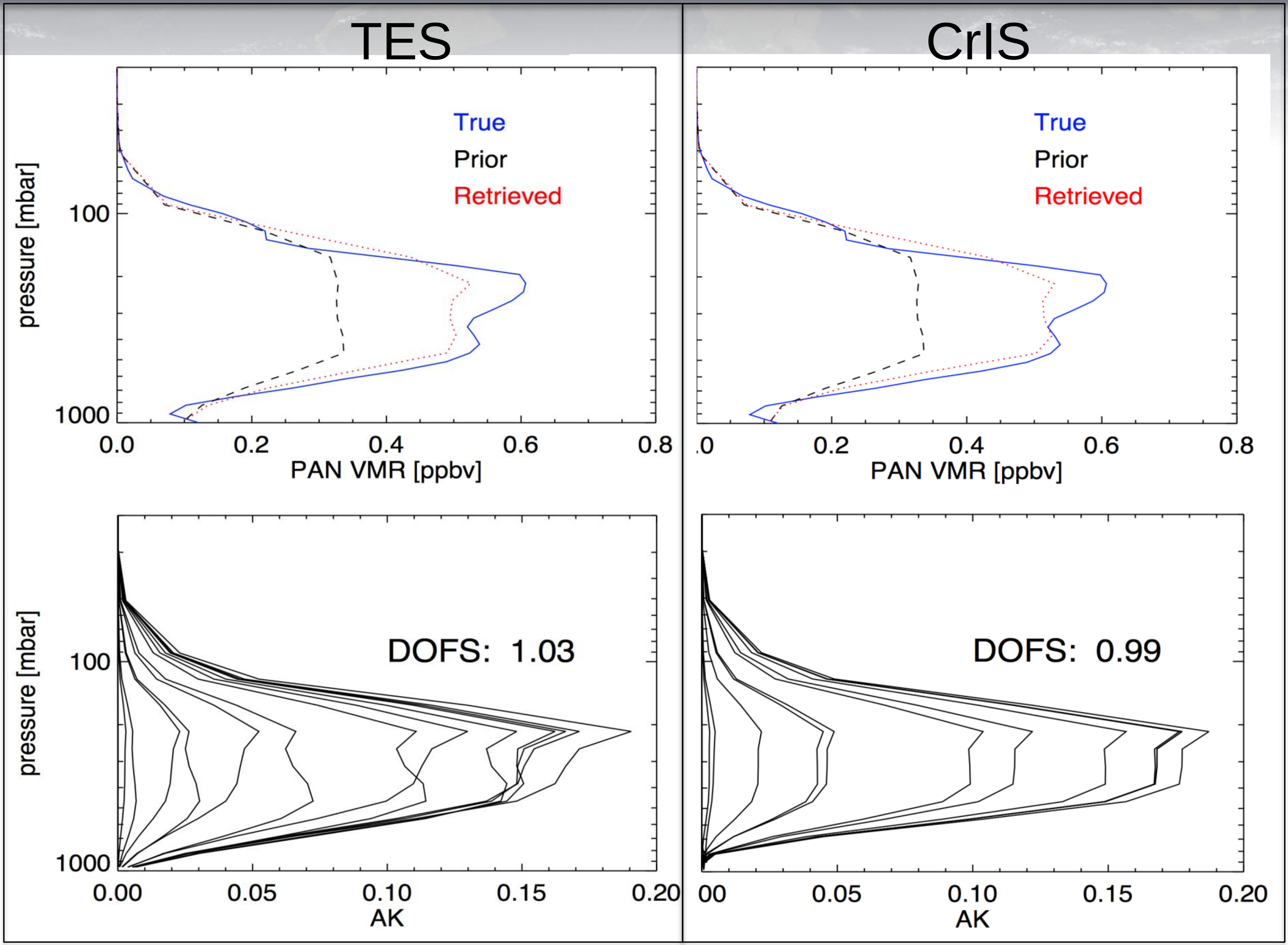
- Value of multiple wavelength regions for vertical sensitivity
  - Joint AIRS/OMI and CrIS/OMPS retrieved O_3 profiles can distinguish the abundances in the upper troposphere from the lower troposphere.

- Opportunities for multi-satellite retrievals to extend EOS-era data records

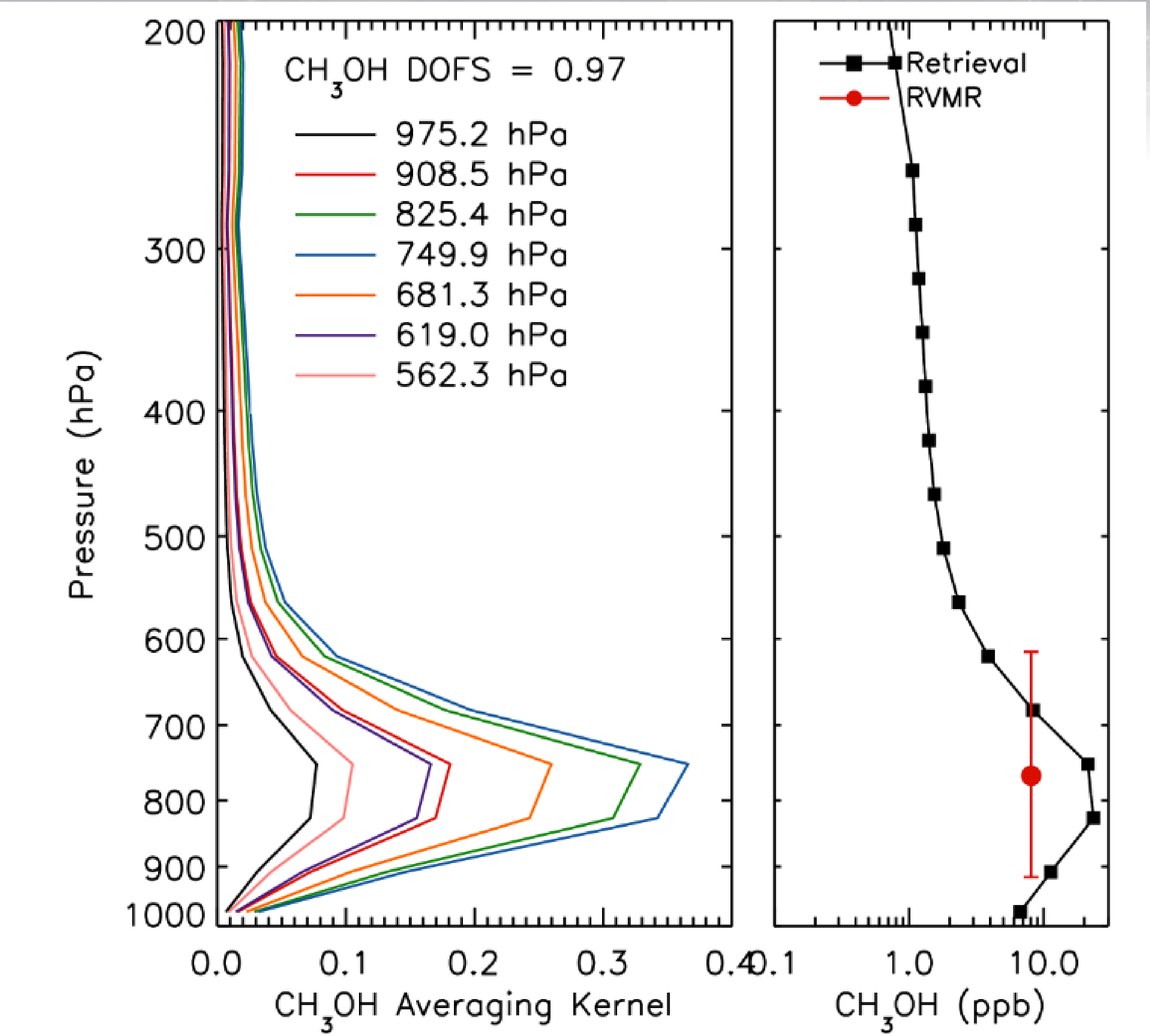
- Observation operators and error estimates are key to the effective utilization of the retrievals.

Backup

PAN from CrIS



TES methanol

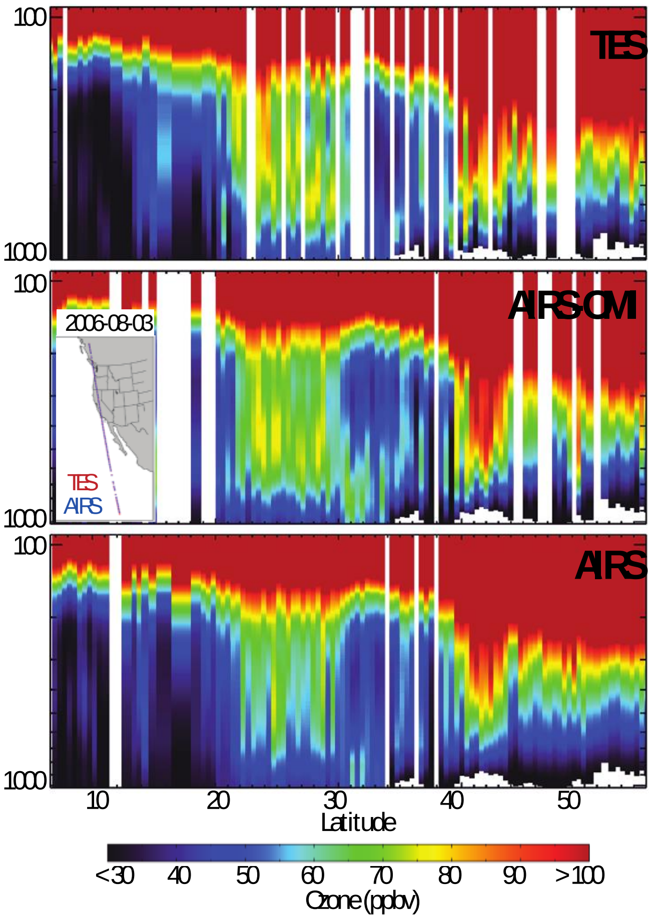


Joint AIRS/OMI and TES observations on August 23, 2006 during TexAQS Aircraft Flight Campaign

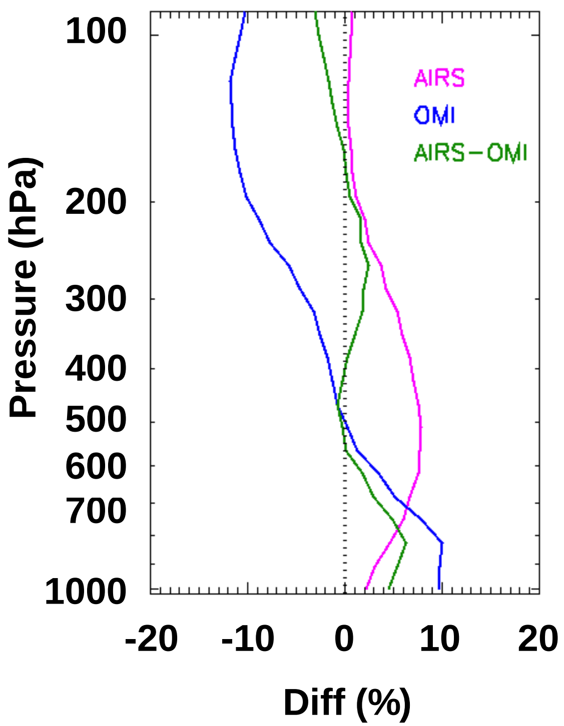
Joint AIRS/OMI ozone retrievals

- Show best agreement to TES, in comparisons to each instrument alone

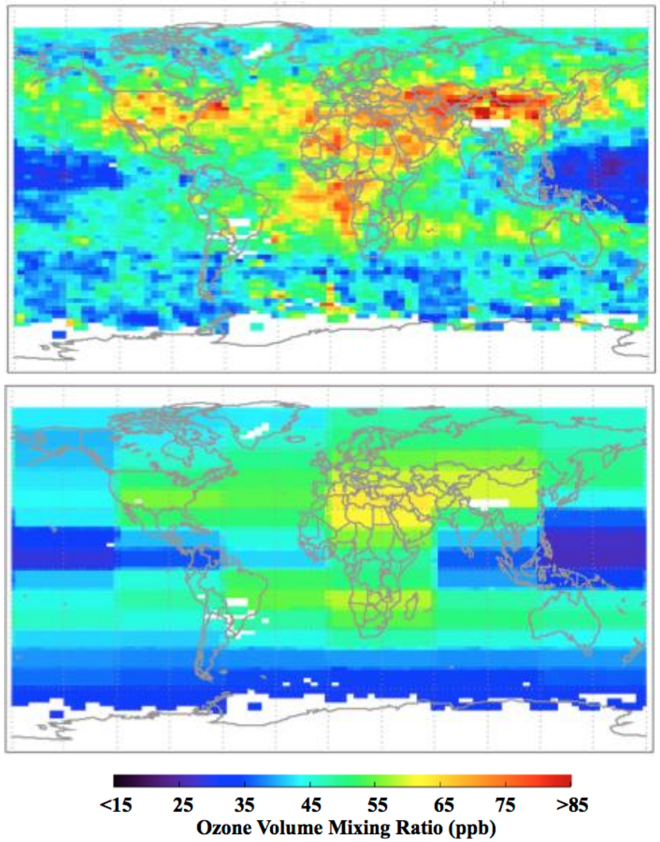
Transect over Western USA



Difference to TES



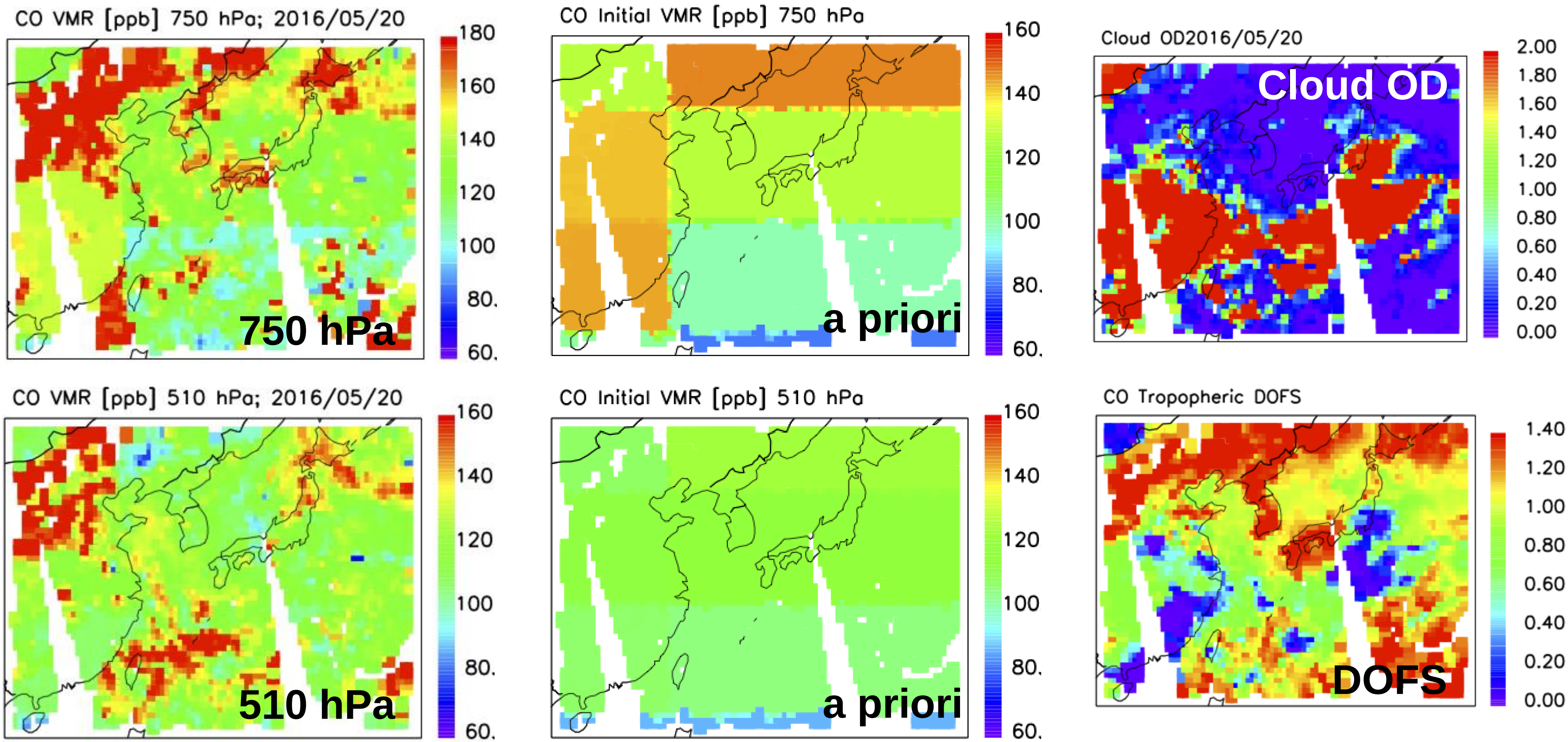
Joint AIRS/OMI O_3 monthly mean @681 hPa



CrIS Carbon Monoxide Maps for KORUS-AQ

CrIS retrievals using JPL MUSES algorithm

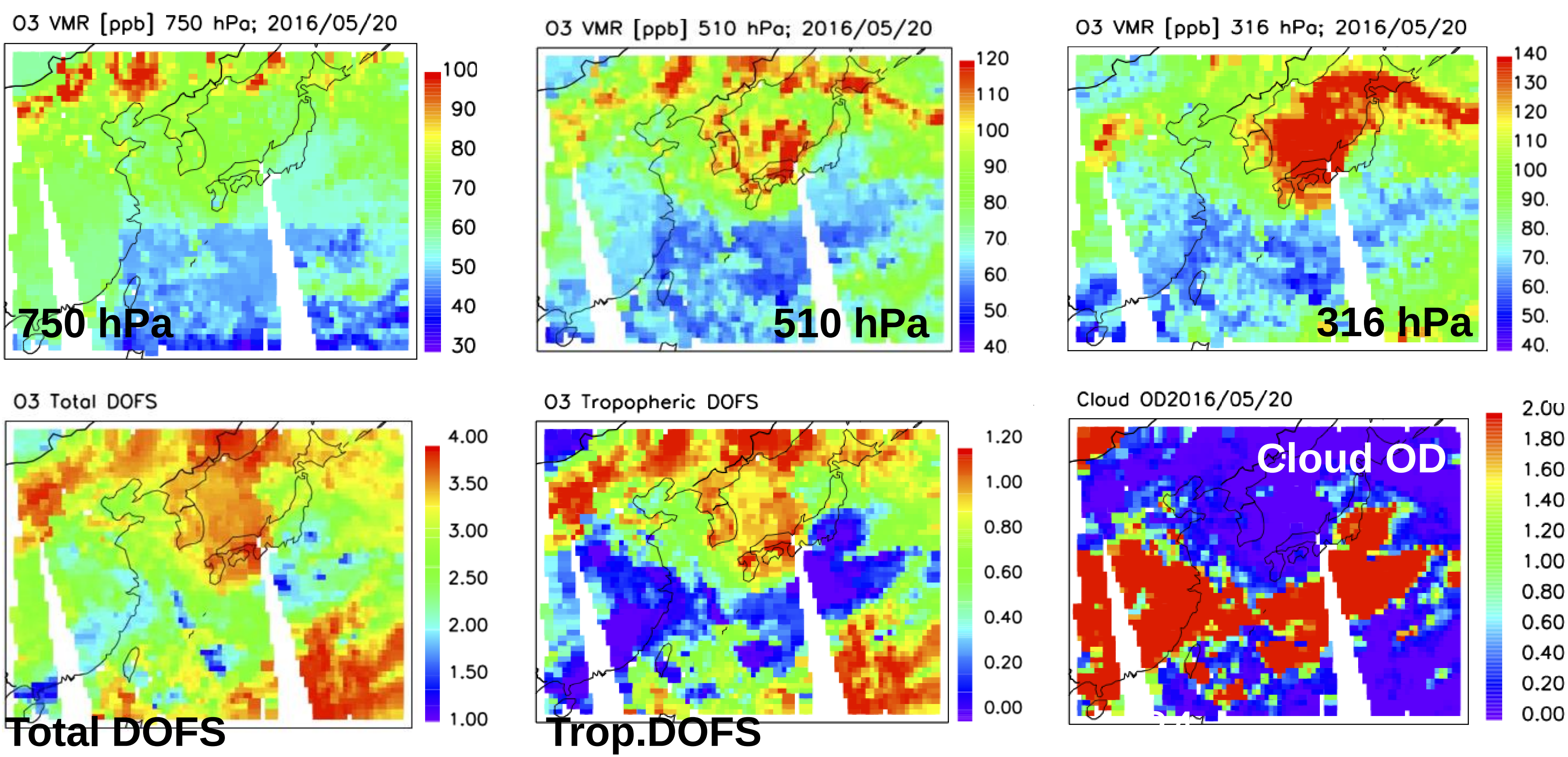
- Nine times higher spatial resolution vs. the CrIS operational data products
- Provides full observation operators (averaging kernels, uncertainty estimates, a priori profiles)
- CrIS alone will be used for extending the MOPITT TIR CO data, while combines TROPOMI measurements to extend MOPITT TIR/NIR multi-spectral CO data.



CrIS Ozone Maps for KORUS-AQ

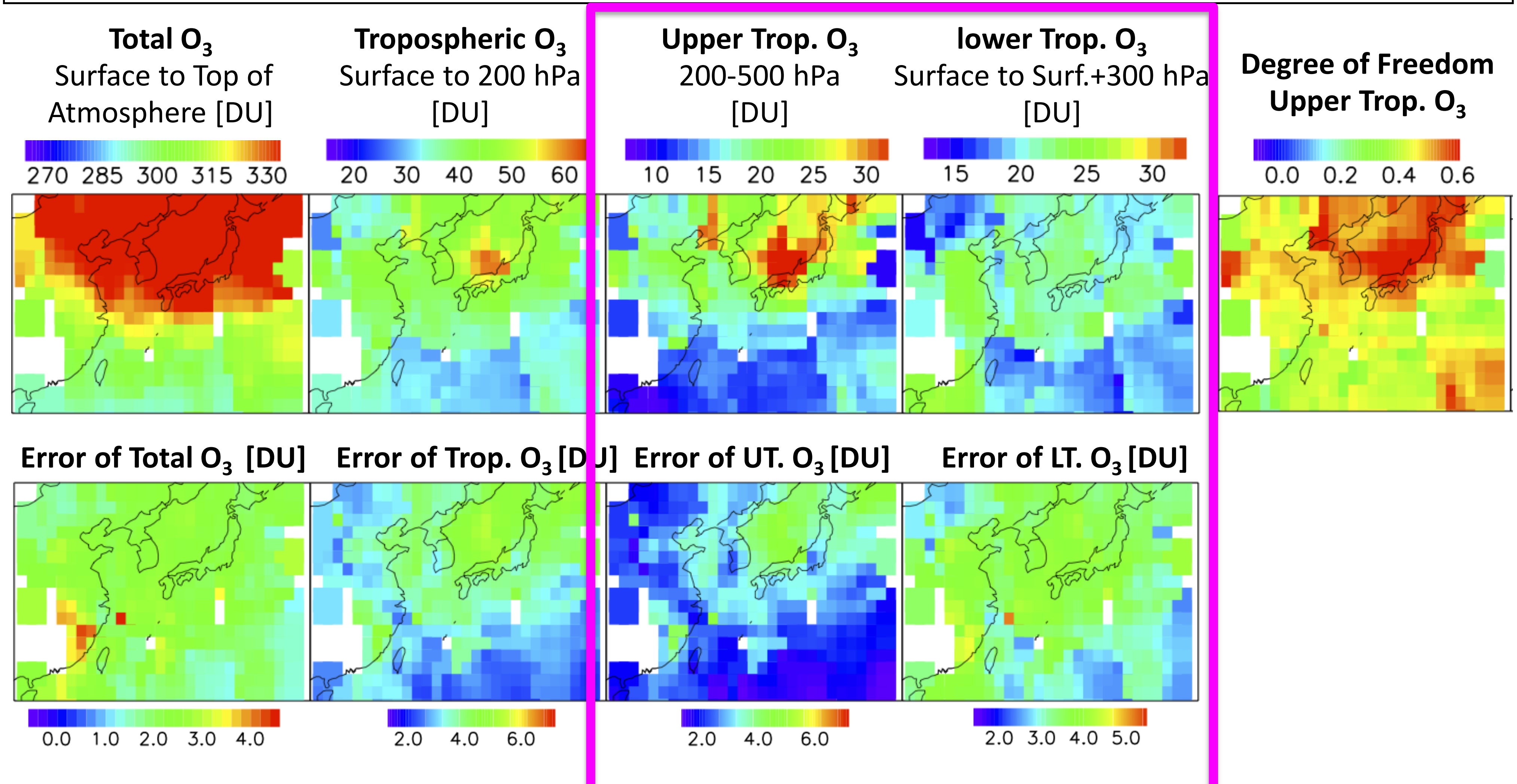
CrIS retrievals using JPL MUSES algorithm

- Nine times higher spatial resolution vs. the CrIS operational data products
- Provides full observation operators (averaging kernels, uncertainty estimates, a priori profiles)
- Working on combining OMPS measurements, joint CrIS/OMPS could improve the spatial coverage by a factor of three, in comparisons to joint AIRS/OMI.



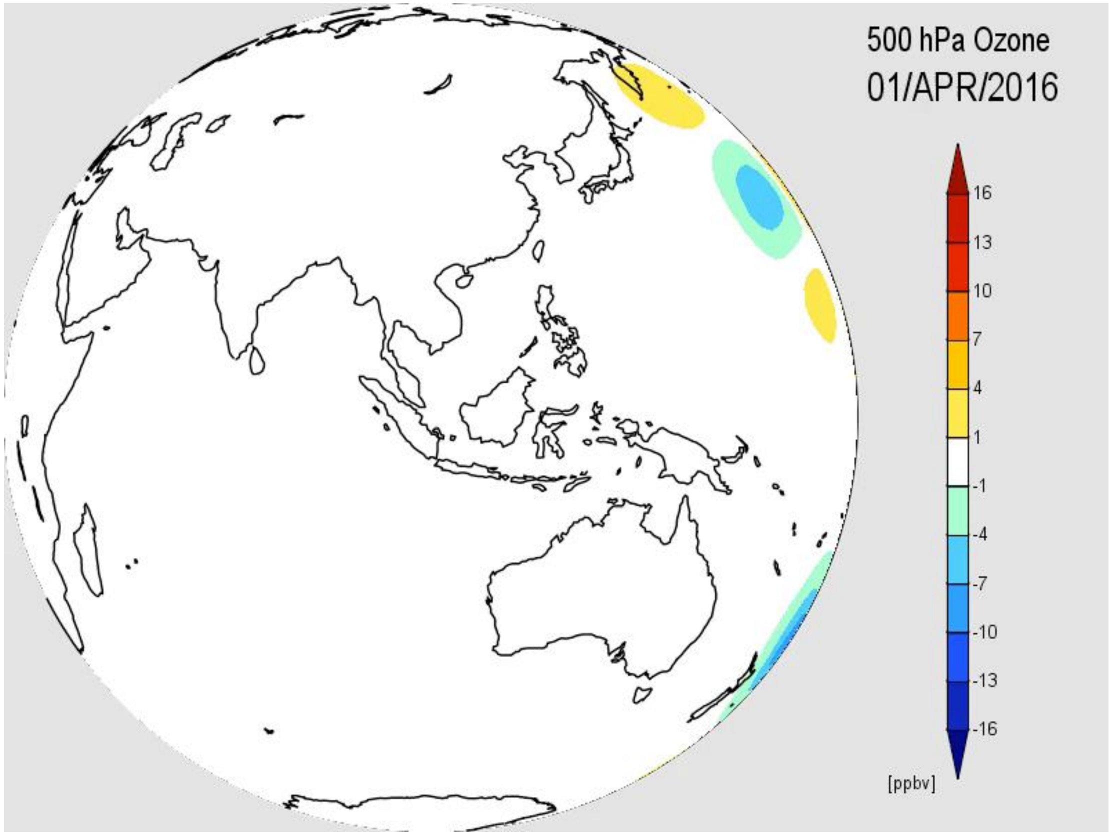
Joint AIRS/OMI O_3 Retrievals

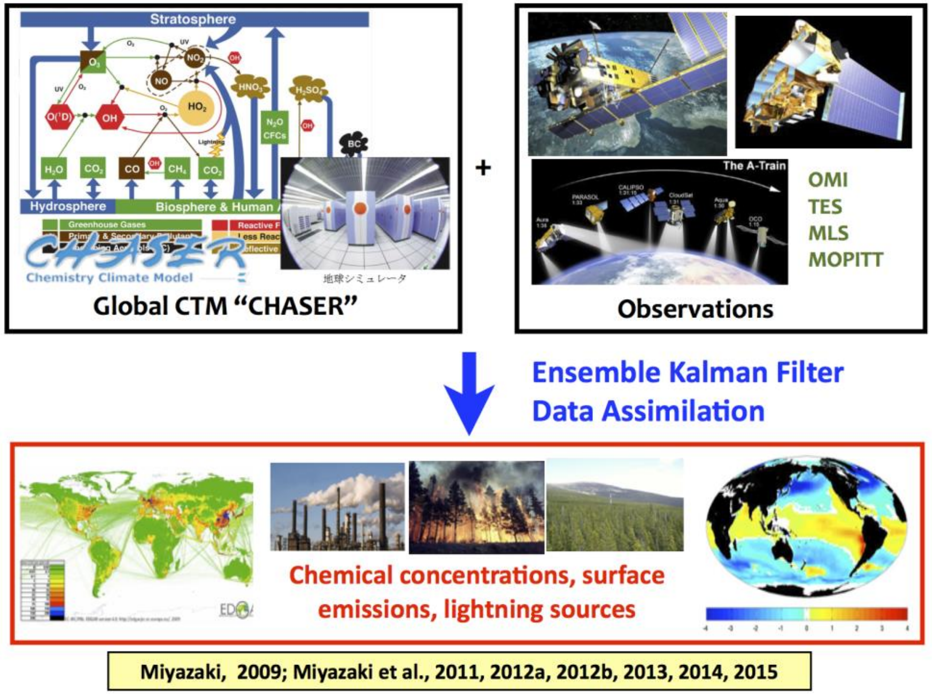
- Retrieved joint AIRS/OMI ozone
  - Three-day averaged, May 18 to 20, 2016.
  - Total ozone shows strong latitudinal dependence, dominated by stratospheric ozone.
  - Tropospheric/upper tropospheric ozone enhancement over the ocean (Korean peninsula <-> Japan), could be the natural influences of stratosphere-troposphere exchange (STE) process.



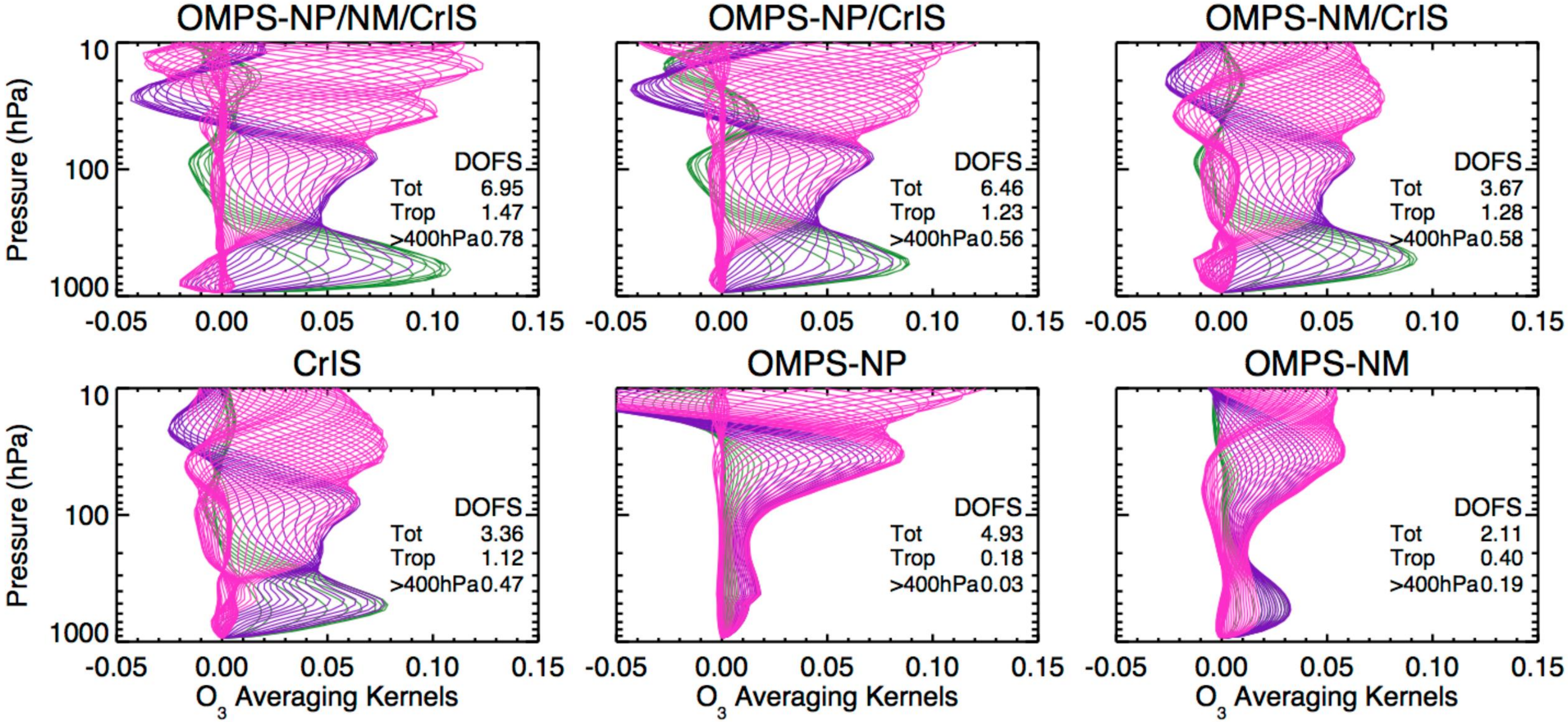
Impacts of Joint AIRS/OMI O_3 Profiles on Data Assimilation

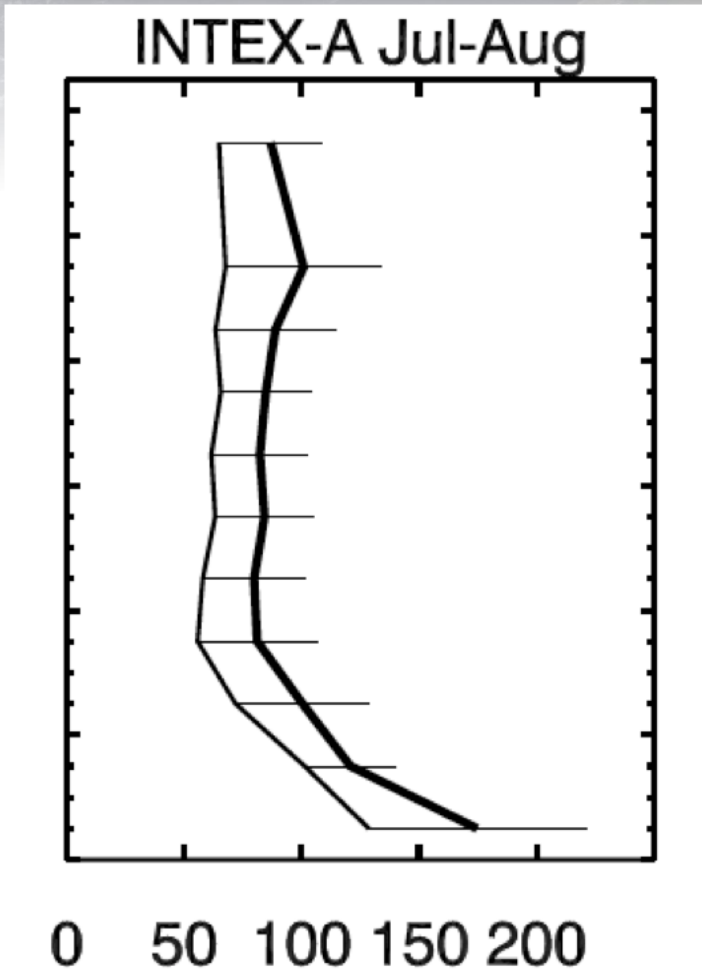
- Joint AIRS/OMI ozone profiles have been assimilated into CHASER system.
- CHASER system assimilated the OMI (NO_2), GOME-2 (NO_2), MLS (HNO_3 and O_3), MOPITT (CO) for KORUS-AQ ,recently assimilated AIRS/OMI ozone profile data





Combining CrIS, OMPS-NM and OMPS-NP




INTEX-A Jul-Aug
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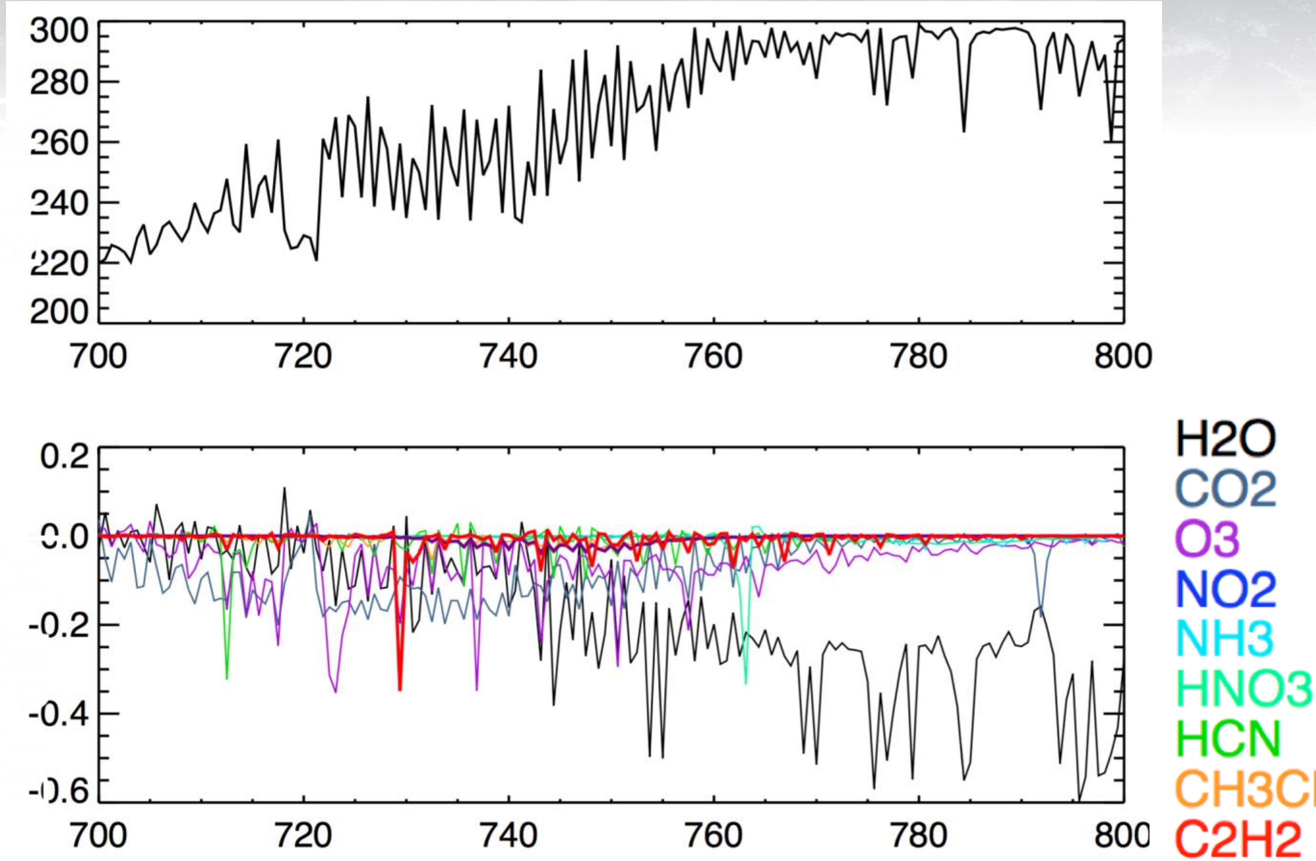
300
280
260
240
220
200
700
720
740
760
780
800
0.2
0.0
-0.2
-0.4
-0.6
H2O
CO2
O3
NO2
NH3
HNO3
HCN
CH3Cl
C2H2

Available trace gas products from **NASA/NOAA** thermal-IR sounders*

Omnipresent

Molecule	AIRS v6	AIRS OE J. Warner et al	AIRS NUCAPS	TES v7	CrIS NUCAPS	CrIS AER/NCAR+
O_3	Y		Y	Y	Y	
O3 IRKs				Y		
CO	Y	Y	Y	Y	Y	+
CH_4	Y		Y	Y	Y	
CO_2	Y		Y	Y	Y	
N_2O		Y	Y	Y	Y	
HDO				Y		
HNO_3		Y	Y		Y	
OCS	AIRS gap	AIRS gap	AIRS gap	Y	CrIS gap	CrIS gap
NH_3		Y		Y		+
CH_3OH				Y		
HCOOH	AIRS gap	AIRS gap	AIRS gap	Y	CrIS gap	CrIS gap
PAN				Y		
SO_2	flag		Y		Y	
C_2H_2						
C_2H_4						

Observable at enhanced concentrations

*Attempt to capture range of products avail – please excuse omissions/misunderstandings
+ Not yet publicly available, but will be in forseeable future